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A new X-ray mission to measure the power spectrum of fluctuations in the Universe

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We propose a new, simple, dedicated X-ray mission to measure the power spectrum of density fluctuations in the Universe, by accurately mapping the X-ray background on the whole sky on scales of $\sim 1\,\mathrm{deg}^2$. Since the method relies on the detection of excess fluctuations produced by the clustering of X-ray sources at intermediate redshifts above the confusion noise produced by bright foreground sources, counting noise and systematic noise need to be kept to a minimum. We propose a proportional counter with collimated fields of view of various sizes as the optimal instrument for this mission.

Key words: The X-ray Background, Large Scale Structure of the Universe.

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1. Introduction

Recent progress in the optical identification of faint X-ray sources discovered in *ROSAT* deep fields shows that the bulk of the soft (0.5-2 keV) X-ray background (XRB) originates at intrmediate redshifts $z \approx 1-2$ (Boyle et al 1994, McHardy et al 1997, Hasinger et al 1997, Schmidt et al 1997). The X-ray volume emissivity of the Universe in the soft band peaks at these intermediate redshifts. This is particularly interesting, since it is at these redshifts where the process of galaxy formation culminates its non-linear growth and where the bulk of star formation appears to happen (Madau et al 1996). Studies of the angular structure of the XRB should be able to map the lumpiness of the Universe at these redshifts.

The distribution of density fluctuations in the Universe on different scales is described in terms of the power spectrum (PS) of the fluctuations $\mathcal{P}(z, k_c)$ (z is the redshift and k_c the comoving wavenumber), which is the Fourier transform of the two-point correlation function. The current information on the PS comes from both local galaxy surveys and from studies of anisotropies in the microwave background radiation (MBR). The former are most powerful on small scales $< 50\,h^{-1}\,\mathrm{Mpc}$ (h is the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) and the latter emphasise large scales ($\sim 1000\,h^{-1}$Mpc) at very high redshifts ($z \sim 1500$) when the amplitude of the PS was very small. Overall fits of the PS can be reproduced by Cold Dark Matter models where the PS presents a broad peak at comoving wavevectors $k_c \sim 0.01 - 0.1\,h\mathrm{Mpc}^{-1}$ (see Peacock 1997 for recent parametrisations).

In this paper we propose a new X-ray mission dedicated to measure the PS near its maximum at the redshifts where the bulk of the XRB originates. There are various reasons to study this specific region of the redshift-wavevector space. The most important one is that, as has been said, it provides a measurement at a redshift in between the very smooth Universe at the MBR epoch and the very lumpy Universe we see today. Moreover, the evolution of the PS between $z \sim 2$ and $z = 0$ is most sensitive to the specific cosmological model (q_0 and Λ). And finally, by selecting angular scales of ~ 1 deg, we are most sensitive to the peak to the PS, where the fluctuations are easier to measure and most useful to define the normalization of the PS.

The precision of intensity measurements of the extragalactic XRB on these scales is dominated by spatial fluctuations caused by confusion noise. Sources with 2-10 keV fluxes $\sim 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ will dominate this confusion noise. The measurement of excess fluctuations produced by clumping of the more numerous, distant sources requires both a precise knowledge of the confusion produced by the foreground sources and also precise measurements of the XRB intensity over the whole sky. Source counts down to a 2-10 keV flux level $< 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$

will be found in the all-sky survey performed by *ABRIXAS* (Friedrich et al 1996). Source variability might be a problem (see later) if large, due to the non-simultaneous observations of the sources and the XRB measurements. Photon counting noise might be a limiting factor in the precision of the XRB measurements, and therefore a large effective area is needed. The requirement that other systematics are kept to a minimum calls for the most stable instrumentation, large effective area and minimal degradation and gain variations over long periods. In what follows, we outline the mission requirements in terms of measurement requirements for cosmological purposes and then study with some detail the case of a collimated field-of-view proportional counter, which is the instrument we propose. We concentrate on the 2-10 keV energy band where the contribution from the Galaxy at high galactic latitude is likely to be relatively small and smooth on scales of ~ 1 deg.

2. Sensitivity to excess fluctuations

The distribution of XRB intensities when measured with a beam of $\Omega\,\mathrm{deg}^2$ is a non-gaussian 'P(D)' curve with various contributions to its intrinsic dispersion $\left(\frac{\Delta I}{I}\right)_{int}$. We explore these contributions in the next section (confusion noise, photon counting noise and systematics) and separate here the excess fluctuations $\left(\frac{\Delta I}{I}\right)_{excess}$ that we intend to measure. These excess fluctuations can be related to $\mathcal{P}(z,k_c)$ weighted by the square of the X-ray volume emissivity ($j(z)$) with appropriate K-corrections. The volume emissivity $j(z)$ is still not known for the 2-10 keV band, but it certainly will be after *AXAF* deep surveys have been performed (by resolving virtually 100% of the XRB) and subsequent optical follow-up with 10-m class telescopes has revealed the redshift distribution of the sources that give rise to the XRB. For the moment we assume that $j(z)$ is similar to the 0.5-2 keV one, which peaks strongly at a redshift $z \sim 1.5-2$ (say $z_c = 1.7$). Roughly speaking, the expected excess fluctuations are

$$\left(\frac{\Delta I}{I}\right)^2_{excess} = \frac{2}{\Delta V}\mathcal{P}(z_c,k_0)$$

where ΔV is the volume of space sampled by a single beam Ω and $k_0 \approx 0.04\Omega^{-1/2}\,h\,\mathrm{Mpc}^{-1}$ is the wavevector at which the angular selection function peaks (see Barcons, Fabian & Carrera 1997 for details). This is very close to the expected peak of the PS, which has the added advantage that small changes in the angular scale produce a negligible change in the value of the PS. To make a significant detection (see Fig. 5 in Barcons, Fabian & Carrera 1997) a sensitivity of less than $\sim 1h^{-3}\,\mathrm{Mpc}^3$ should be achieved in terms of the power spectrum. The volume sampled by a beam is of the order of $10^5\,\Omega\,\mathrm{Mpc}^3$, and therefore excess fluctuations of less than $5\times10^{-3}\Omega^{-1/2} \sim 0.5\%$ should be measured for a detection.

The minimum value of the excess fluctuations that can be measured when N_{obs} independent measurements of the XRB are performed is

$$\left(\frac{\Delta I}{I}\right)_{2\sigma} = \sqrt{\frac{2}{N_{obs}}}\left(\frac{\Delta I}{I}\right)_{int}$$

As we shall see in next section, to achieve a value of a few $\times10^{-3}$, this requires $N_{obs} \sim 10^4$, which means approximate all-sky coverage for a $\sim 1\,\mathrm{deg}^2$ beam.

3. A collimated field of view proportional counter

In this section we evaluate the budget of contributions to the intrinsic dispersion of the distribution of XRB intensities, for a collimated field of view proportional counter with effective area $10^4 A_4\,\mathrm{cm}^2$, exposure time per pointing $100 t_{100}\,\mathrm{s}$ and beamsize $\Omega\,\mathrm{deg}^2$.

3.1. Confusion Noise

Assuming an euclidean power-law for the bright source counts in the 2-10 keV band (Piccinotti et al 1982, Gendreau, Barcons & Fabian 1997, Georgantopoulos et al 1997, Cagnoni, Della Ceca & Maccacaro 1997), the contribution to the intrinsic dispersion from confusion noise should be

$$\left(\frac{\Delta I}{I}\right)_{confusion} \sim 0.13\Omega^{-1/3}$$

Table 1: Summary of requirements for the proposed mission

Instrument	
Gas-filled proportional counter	
Collimator FOV	$0.5 \times 2\,\mathrm{deg}^2$
	$1 \times 2\,\mathrm{deg}^2$
Effective area	$\sim 1000\,\mathrm{cm}^2$
Energy bandpass	$\sim 2 - 10$ keV
Accuracy in measuring XRB	$< 3\%$
Mission/Payload	
Expected lifetime	> 2 years
Stabilization	One axis
Orbit	Equatorial

Since our goal is to measure fluctuations almost 100 times smaller than this, this number should be known with a few per cent accuracy. The *ABRIXAS* all-sky survey will provide the required accuracy, but two systematic effects should be carefully taken into account.

3.1.1. Source Variability

Variable sources produce a systematic effect in the determination of source counts in flux-limited samples (Barcons, Fabian & Carrera 1997). Assuming varability within a factor of 2, this bias is of the order of 1%, but for a factor of 5 variability this amounts to a 5% effect (assuming euclidean counts). This effect can be corrected for if known. That should be possible in *ABRIXAS* at least for the brightest sources, since the sky will be scanned several times.

3.1.2. Spectrum of bright sources

Since the spectral responses of the instrument proposed and *ABRIXAS* (with which the source counts at bright fluxes will be found) are different, there will be an indetermination when translating the source counts, particularly with highly absorbed sources. This could be resolved by examining a sample of bright sources detected with our instrument. A comparison with observations of *ABRIXAS*, should be able to remove most of this uncertainty.

3.2. Photon counting Noise

Events detected in a proportional counter come from both X-ray and charged particles passing through the detector. Since both fluxes scale differently with the field-of-view solid angle, it is crucial to have at least 2 different collimator sizes for accurate particle background subtraction (Boldt 1987).

The counting noise resulting from both components has been estimated by using 'clean' sequences from both the *Ginga* LAC and the *RXTE* PCA, resulting in

$$\left(\frac{\Delta I}{I}\right)_{counting} \approx 0.024(A_4 t_1 00)^{-1/2} \left[\frac{1}{\Omega} + \frac{1}{\Omega^2}\right]^{1/2}$$

3.3. Systematics

One of the key issues is the stability of the particle background. Experience accumulated with *Beppo*SAX suggests that an equatorial orbit is the best choice for this purpose. As already said, having at least two different collimator sizes will allow accurate subtraction (as opposed to modelling) of the particle background.

Stochastic gain variations in the proportional counter are the most unpredictable source of systematics in our study. Long term drifts can be monitored and modelled appropriately with the observations themselves, if the product $A_4 t_{100}$ is large enough. For $A_4 t_{100}$ around 1, the statistical accuracy in the measurement of each measurement of the XRB towards each direction will be of the order of 3%. Long-term gain variations should be detectable to a precission much better than this, but this requires a large enough collecting area.

4. Conclusions

Our proposal for measuring the peak of the power spectrum of the fluctuations in the Universe at intermediate redshifts and comoving wavevectors $k_c \sim 0.01 - 0.1\, h\,\mathrm{Mpc}^{-1}$, consists of a mission which would scan the whole sky several times (at least 4) with a proportional counter. At least two different collimated field of view sizes should be available to give a clean sky signal. To have a maximally stable particle background, an equatorial orbit would be most desirable. A large effective area (close to $10^4\,\mathrm{cm}^2$) is required to model long-term gain variations. Table 1 summarizes the main requirements for this mission.

The proposed mission is tecnologically very simple. Proportional counters are the most tested and stable X-ray detectors. A slightly modified version of the *Ginga* Large Area Proportional Counter, with two different collimator sizes, would certainly be good enough for our purposes. Also the requirements for the payload would be minimal, since no 3-axis stabilisation would be needed during the all-sky scans.

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